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Research accomplishments were in shock-vortex interaction and in a number of studies in grid generation. These studies included algebraic, adaptive, surface, and interactive grid generation. The algebraic and interactive aspects converged with the establishment of a powerful control point formulation for arbitrary grid generation. Selected publications include: "Adaptive Grid Generation"; "Adaptive Grid Solution for Shock-Vortex Interaction"; "Grid Generation for the Solution of Partial Differential Equations"; and "A Control Point Form of Algebraic Grid Generation."

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INVESTIGATION OF THREE-DIMENSIONAL MESH GENERATION WITH PRECISE CONTROLS

by

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INVESTIGATION OF THREE-DIMENSIONAL MESH GENERATION WITH PRECISE CONTROLS

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OVERVIEW

In the grant, a number of accomplishments were made in a variety of ways and in a variety of topics. The ways in which this was achieved were in the oral communication with others, in the organization of conferences, in the journal publications, in the direction of graduate studies, and in the computer demonstration of theoretical developments. The topics included a study of shock-vortex interaction and a number of studies in grid generation. Those studies covered algebraic, adaptive, surface, and interactive grid generation. The algebraic and interactive aspects here converged with the establishment of a powerful control point formulation for arbitrary grid generation.

LECTURES ON GRIDS

In the middle of the grant, the principal investigator was in Europe at the Dutch Numerical Mathematics Conference where he had been a principal invited speaker. To take advantage of the fact of his presence in Europe, he had also arranged to visit several other organizations. The respective visits were to NLR, the Dutch National Aerospace Laboratory in Amsterdam, and to Dornier, the German aircraft company in Friedrichshafen which is not too far from Zurich.

The respective advantages of these visits were twofold: first, an open and cooperative dialogue was established between our efforts and secondly, it provided immediate information on the level of their developments as well as their various technical aspects and points of emphasis. For instance, at Dornier,

the emphasis placed upon interactive grid generation in the block structured format was significant and was a key element of their capability to obtain simulations about realistic aircraft. In our own subsequent development this provided some further motivation to develop a substantially stronger tool for interactive grid generation: the control point form of algebraic grid generation. PP Based upon the lectures presented in Europe and slightly earlier in Texas, two invited review papers were written. In each of these reviews, a serious attempt was made to consolidate and synthesize the material rather than to present an array of topics in a somewhat unconnected manner. Moreover, in the course of presenting a coherent discussion, a number of new ideas were set fourth: this primarily occurred in the topic of adaptive grid generation and to a lesser extent on other topics.

AN IN DEPTH REVIEW OF ADAPTIVE GRID MOVEMENT

The adaptive grid paper [1] was concerned with the analysis development, and implementation of grid point motion for the purpose of dynamically increasing the accuracy of numerical simulations of physical processes. Although these are primarily taken from fluid mechanics with a particular emphasis on aerodynamics, they also apply a wide range of other fields. The general philosophy of the discussion therein is to present an overview of the subject and at the same time to impart an operational knowledge base for the reader should there be a desire to actually try out some of the ideas.

In accordance with the desire to consolidate the various activities in adaptive grid point motion, the process under discussion was decomposed into subtopics that are commonly executed in different manners but are fundamentally the same. The first subtopic is the question of how to express the adaptive data. This occurs with either formal error estimates or with a monitor surface which consolidates the rapidly varying parts of the desired solution. In the latter context, the grid generation can be done either on the monitor surface or on its projection into physical space. Regardless of where the generation occurs, the basic action comes from the equidistribution of a suitable weight function. Thus, whether error indicators or the geometric features from a monitor surface are employed, the essential active elements of the motion must be put together at this stage.

Of the various possible weight function formulations, the general linear format is the one that is commonly employed and as a result this is examined with some care. The next subtopic is the equidistribution process. This is examined in 1-D in considerable detail from a dozen distinctive viewpoints. The reason is

that equidistribution is the basic active element of most methods and its essential features are most directly witnessed in 1-D. Next, three attractive attributes from linear weights are exploited regardless of the chosen form for equidistribution. In a similar spirit, we discuss three ways to attract points to a given grid and four ways to insert evolutionary forces.

With the basic elements established in 1-D, we next proceed to develop the higher dimensional methods and to consider the temporal coupling. In our categorization, the methods are split into curve by curve, finite volume, and variational methods. The discussion comes to an end with a conclusion that provides a brief overview. Upon examination of the overall structure of the review, it is evident that by considering the various alternatives within each subtopic, we have not only covered all of the existing works of the time but also those works yet to be done by utilizing other combinations of the various alternatives.

While the above combinations certainly provide a source for further developments, additional new ideas have been derived within the subtopics. The most prominent of these is the establishment of a general parabolic PDE that can smoothly drive the grid with both curve by curve and evolutionary controls. The parabolic nature comes about by setting a scaled time derivative equal to a spatially elliptic operator. This system was derived from a variational statement as the associated Euler equations. Moreover, this system represents a more formally correct extension and consolidation of two apparently distinct works of Anderson together with the incorporation some temporal controls from Winkler.

As a consequence of this review, the Poisson forcing terms derived by variational means have found their way into several large codes that also have been now formally reported. These are the EAGLE code developed by Thompson et al [2] and the General Dynamics Code developed by Steinbrenner and Anderson [3]. Other smaller scale results have also been reported, one of which was reported by Eiseman at SIAM (and delivered by C. W. Mastin) as [4].

A COMPREHENSIVE REVIEW OF NUMERICAL GRID GENERATION

Unlike the adaptive review paper above, the second review paper [5] represents a broad coverage of the entire field of grid generation. As such, the previous in depth discussion was not attempted for that would more appropriately be suited for an entire book rather than for only one chapter in a book as per the invitation of A. K. Noor. This review was undertaken with my

former doctoral student, G. Erlebacher.

As in the adaptive review, the subject was split into suitable subtopics that were ordered in a logical fashion. After a general overview in the introduction, the subtopic of connectivity patterns was examined to set the foundation on which the various methods are to be developed. This involved structured, unstructured, and partially structured patterns. Within the structured patterns, the discussion was organized so that the various forms of assembly were made to appear with increasing levels of continuity. With the choice of a pattern, a grid topology appears and the data base for the generation is established.

Accordingly, the methods of generation are considered next. The first methods are the structured ones. These basically consist of algebraic and PDE methods which may be respectively thought of as explicit and implicit methods. The algebraic development leads up to the multisurface transformation and then proceeds to consider the transfinite assembly of directional constructs. The PDE development is considered in the progressive stages separated by increasing the severity of constraining requirements which typically enter as boundary conditions. Accordingly, the story starts with hyperbolic methods and progresses towards elliptic methods where more control is available.

After an inspection of unstructured techniques, we move on to the subtopic of interactive grid generation. The main focus on interactive methods is on structured grids. The last subtopic before we reach a conclusion is that of adaptivity. This is examined from both structured and unstructured viewpoints and with both grid movement and alterations in the number of points.

Altogether, this review represents probably the most organized discussion of the topic of grid generation that is currently available and also provides a substantial list of references. While these references are not comprehensive, they do provide a ready access to points where further discussion on the principal ideas can be found.

As of the writing of this report, the review has yet to appear as a chapter in the intended ASME book. This delay has occurred because of the detailed requirements of going through the "proofs" for the type-setting for several iterations. This is perhaps, because the book is one of the very few that ASME is having type-set over several years. Nonetheless, the review has unofficially appeared as an ICASE report. This occurred because

ICASE has distributed close to a thousand copies. As a consequence, the review has now been heavily referenced even though it has not officially appeared!

ALGEBRAIC AND INTERACTIVE GRID GENERATION

A significant theory was established for the future development of algebraic, interactive, and adaptive grid generation. This has all occurred with the creation of a control point formulation for algebraic grid generation [6]. The reason why it is significant is that the coordinate transformation, as a continuum, is highly controlled by a relatively sparse net of control points. The basis of the control comes both from the local action of each control point and from the strong convexity property of the constructs for each direction. All of this occurs simultaneously with the capacity to precisely specify any number of boundaries while leaving the rest open for free-form manipulation.

The convexity is a direct result of the utilization of multisurface transformations. This occurs because those transformations are based upon an interpolation of the basic tangent field to the desired coordinate curves. As such, the change in curve direction is well modeled. This then means that the the curvature of the associated coordinate curves is highly controlled. In the given direction of construction, the curvature control is essentially the best that can be expected for the chosen number of control surfaces.

To most directly achieve this control in all directions, we could consider a transfinite assembly that would clearly permit us to conform to all boundaries as well. However, this would entail a rather large amount of storage and manipulation. These extensive requirements arise from the need to use entire control surfaces, each of which reflects the same level of complexity as its somewhat parallel boundaries. Although those control surfaces can be given simplified structures, the user is burdened by the need to create them. The intensity of this burden increases with dimensionality. In 2-D, the user must deal with entire curves; in 3-D, entire surfaces. As a consequence, our assembly avoids these somewhat stringent demands and retains the essential features of the desired control. The result is a transfinite conformity with the boundaries together with a tensor product core that provides the basic sparse net of control points.

Unlike the direct use of a transfinite assembly, the boundary conformity can be applied selectively rather than being constrained to apply to only opposing pairs of boundaries.

Moreover, the basic virtues of the convexity control are preserved. But all of this is done with a very small data set. As a consequence, we now have a ready vehicle upon which we can build an effective interactive grid generator. This occurs because the sparsity of the data places much more modest demands upon an interactive user. Also because of the reduced data set, the further application to adaptive grid generation is evident. In the adaptive context, there can clearly be a fair amount of effort expended at each control point without causing a disastrous amount of labour and thus an excessive amount of consumed computer time. As a consequence, variational techniques that were unattractive because of their cost but were attractive because of their clarity in statement can now be seen as fully viable instruments when applied in the context of the control point form of algebraic grid generation.

While the potential use of general variational constructs is evident, the development of graphically interactive schemes is a first consideration. The interactive environment is the most direct means to reap the advantages of the control point formulation and is not totally divorced from variational methods, but rather provides an intermediate path whereby such methods can be employed in perhaps, a more restricted sense. Accordingly, an interactive development was started for the purpose of generating grids for problems in turbomachinery. This subsequent development has occurred at NASA Lewis Research Center. In particular, an interactive code has been written for single block 2-D grids for cascades of compressor or turbine blades. The grid topology, there, is of the C-type. That development is formally reported by Choo, Eiseman and Reno [7], Choo, Soh and Yoon [8], and Eiseman [9].

ADAPTIVE GRID SOLUTION OF SHOCK-VORTEX INTERACTION

In the confines of adaptive grid generation, research has been steadily progressing in the development of and application of the alternating direction method. This work was done with my student Michael Bockelie who received his PhD in October 1988. Our primary aim was to adaptively model and more deeply study the process of shock-vortex interaction.

In terms of our algorithmic development, our research initially occurred in a somewhat parallel fashion: we simultaneously developed both an Euler equation solver and a grid generator. This was a successful path since both the solver and the generator were more effectively examined without mixing their problems together at a premature stage. This permitted us to refine each to the point where it became reasonable to consider their

coupling without having to worry about problems that pertain to each component in particular.

In setting up the solver part by itself, we simulated the physical problem on a non-adaptive but dense grid. This focused our attention on the development of appropriate boundary and initial conditions. It also allowed us to simulate the entire shock-vortex interaction in a more simple manner. Here, a Mach 3 shock is hitting a specified approximation of a fat core vortex. The physical effect is that the vortex is deformed, is convected downstream, and is seen to generate sound waves. It is the presence of sound wave that peaks the interest in the problem. This simulation represents the fundamental mechanism by which noise is generated from a jet exhaust. There shock waves within the plume smash into the shear layer bounding the plume. It is within the shear layer that the vorticies are present which then naturally leads to our problem.

The whole process is modeled in a time accurate sense but displays a spatial smearing of the severe solution features. This is, of course, to be expected since there is no attempt to consider shock fitting as has occurred in all of the known previous work on this problem. By contrast, however, the use of shock capturing with its concurrent smearing problem is a more general approach which holds out the important prospects of being able to also dynamically model the interactions when the configuration of shock waves have a more involved and complex structure. Altogether, the smearing presents us with a somewhat fuzzy picture of the physical process and our objective is merely to sharpen that picture.

Our tool for this sharpening is the adaptive grid. With its implementation, we modeled the shock with comparable accuracy to the earlier detailed fitting of it and at the same time also provided a crisper resolution of the vortical motion. In the development of the adaptive grid generator, the use of curvature and orthogonality underwent improvements. In addition, the passive smoothing phases were brought into the context of discrete data sets and the monitor surface construction was refined.

Of particular note here is the use of a 2-D surface that is embedded in 4-D. With the shock and the vortex each representing separate disturbances, they are effectively separated in the form of being each an independent coordinate. Thus, when appended to x and y we find our surface as a 2-D object in 4-D. Upon uniformly coating this surface with points all gradients are automatically resolved when those points are projected back to form a grid in (x,y). In this process, we found that there is a

clear separation of the resolution requirements in the sense that severe variations for the shock cannot be depreciated by those for the vortex and vice versa.

In addition, we have also found that the grid structure is automatically improved and thus the need for an active control of orthogonality is greatly lightened. This is rather nice since the control of orthogonality can be expensive relative to the overall cost of grid generator. Of course, the eventual cost is the total one for the entire coupled simulation and accordingly the cost of the adaptive movement will vary in importance with the physical problem being simulated.

With a solver appropriately tuned to our physical problem and with a reliable adaptive movement scheme, the next logical step was to develop the means to utilize each without a concurrent requirement to effect special changes within each. Altogether, the task at hand was to establish a widely applicable and reliable coupling scheme. This was done with a sort of predictor-corrector approach. In the predictor stage, a provisional solution is generated over a interval consisting of a number of computational time steps. From the provisional solution over the time interval beyond our current state, a monitor surface is constructed to represent the severe solution variations in a manner that provides the correct anticipatory resolution together with a smooth transition from the previous resolution. This latter objective is achieved by utilizing solution data from a few earlier time steps. Using the monitor surface, a grid is then generated and the solution data is transferred from the old grid to the new grid. At this stage, we enter the correction phase whereby the solution is regenerated by employing the new grid. The computation thereon is executed up to but not exceeding the physical time from the prediction phase. While at first glance, it appears that this process would double the computational effort, it should be noted that the predictor phase can and should be executed on a coarser grid. In particular, by removing every other point, we save a factor of 4 in 2-D and another factor of two in time for an overall factor of 8. This accordingly reduces the cost of the predictor to an insignificant level.

The adaptive simulation of the shock vortex problem has been formally reported by Bockelie [10], Eiseman and Bockelie [11]-[13]. In addition, the use of evolutionary controls to establish the capability for local adaptivity was demonstrated by Bockelie and Eiseman [14]. This provided an explicit example from the theory set forth by Eiseman in [1].

A task that should be considered in the future is a development of time accurate local time stepping for explicit solvers. This latter topic is, by itself, an important issue. This would permit us to take advantage of explicit solvers while not being severely restricted by stability concerns when the adaptive movement creates smaller local grid sizes for the purpose of resolution. While local time stepping has already been considered, that consideration has only been for the rapid convergence to a steady state: the effect of a direct application of an existing local time stepping procedure is then to create warped time surfaces that at any iteration cycle then produces a distorted image without any physical meaning. To date there is no time accurate local time stepping procedure for dynamically adaptive grids where cells will evolve with smooth gradations from large to small so that desired local regions can be resolved while not causing a slow down due to a global time step arising from the smallest spacing.

SURFACE GRID GENERATION

In the area of surface grid generation, work has progressed with my other doctoral student, Yi Wang. Our objective is to create a means to automatically establish surface grids in a general block-structured context. A key attribute is the capability to provide curvature clustering along with other structural and clustering requirements.

By using the block-structured format we have developed a tool for the treatment of complex topological configurations in a form that is compatible with many other investigators. Quite simply, a major trend has been to develop flow solvers and associated grid generators in a block-structured format. With this trend, however, there has been no real emphasis on the development of a high quality surface grid generator as in our study. This situation has arisen primarily because there has been a race to establish completely assembled packages for block- structured codes rather than to consider any given part in a high quality manner. The result is a real need for good parts.

The most important part of such packages is the surface grid generator. It is also the most difficult aspect of the entire grid generation process. In our approach, mean value relaxation has been exploited for grid point movement on surfaces. The primary action comes through the use of suitable weight functions to accomplish the desired clustering and structural improvements.

The first test cases for our generator were brick-like objects. These were given in an analytical form by employing

superellipsiods. The only change in analytical form from regular ellipsoids is the replacement of the exponent of 2 by an arbitrary number N. As N increases beyond 2, we monotonically converge to a Cartesian box with sharp edges. As the approach to the box becomes closer the edge curvatures increase while the object is still smooth in the sense of differentiability. All of this has provided us with a means to consider severely curved surfaces in a simple way. Accordingly, our first test cases used this. The first one was a single brick with six coordinate patches. The second one was two intersecting bricks with the same grid topology.

Then we moved on towards a realistic configuration: namely, that of a fighter aircraft. We started with a a discrete aircraft description in the form of a fixed given grid. The sole purpose of that given grid is to adequately represent the aircraft. Our task was to then choose a grid topology, to algebraically generate an initial grid for that topology in parameter space, to consider the original given fixed grid as a surface defining map, to apply that map to get an initial surface grid in the desired topology, and finally to dynamically move grid points into optimal positions.

The first part of the development was to restrict the grid topology to be that of the given grid and to consider only part of the aircraft. That part consisted of the canard and the fuselage portion containing the canopy. After success on this case, we move on towards the full aircraft and could not generate the grid on our workstation: it simply required too much computer time. To overcome the time problem, we then created a simple multi-grid type of process. After that, we were able to generate the grid for the whole aircraft on our workstation. Up to this stage, the main action was simply to move the original grid into better positions by dynamic curvature clustering. From, we next considered the whole aircraft with a different topology: in particular, one that conformed more closely with the canopy. With the change in topology, we have the capability to address any arrangement of points on any surface. As an end result, the generator represents a general tool that will be readily amenable to most 3-D block structured grid generation programs and their associated flow solvers. The development with surface grids was formally reported by Wang and Eiseman [15].

In a further development, the surface grid generator has been used in the generation of a 3-D block structured grid where curvature clustering appears on the surface of the aircraft. Currently, the compressible Euler Equations are being solved on this grid and consideration is also being given to including

solution adaptivity along the surface.

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